Series combination of a switched dc-dc converter and a linear regulator for high frequency RF envelope amplifier

O. García, M. Vasic, P. Alou, J.A. Oliver, D. Diaz, P. Cheng, J.A. Cobos

(o.garcia, miroslav.vasic, pedro.alou, jesusangel.oliver, daniel.diaz, pengming.cheng, ja.cobos) @upm.es

Centro de Electrónica Industrial
Universidad Politécnica de Madrid
José Gutiérrez Abascal 2, 28006 Madrid
Spain

Abstract—Classical linear amplifiers such as A, AB and B offer very good linearity suitable for RF power amplifiers. However, its inherent low efficiency limits its use especially in base-stations that manage tens or hundreds of Watts. The use of linearization techniques such as Envelope Elimination and Restoration (EER) allow an increase of efficiency keeping good linearity. This technique requires a very fast dc-dc power converter to provide variable voltage supply to the power amplifier.

In this paper, several alternatives are analyzed to implement the envelope amplifier based on a cascade association of a switched dc-dc converter and a linear regulator. A simplified version of this approach is also suitable to operate with Envelope Tracking technique.

I. Introduction

The solutions for the high frequency power amplifiers can be classified two different families of power amplifiers: linear and nonlinear. The linear power amplifiers (PA) A, B or AB are known to be highly linear, but inefficient solutions especially if the average amplitude is small compared with the supply voltage. On the other hand, the nonlinear power amplifiers have high power efficiency and their output is a sinusoidal signal with constant envelope. They are based on the idea to use transistors as switches instead as a current source. In that way the power losses of the devices are lower and these amplifiers are presented with classes C, D, E and F.

In order to increase the spectral efficiency, the modern telecommunication systems use complex modulations that are based on multicarrier signals and result in complex envelopes that require high linearity. These envelopes have high peak to average power ratio and therefore the linear power amplifiers have extremely low efficiency.

The Kahn's technique [1-2] has showed that it is suitable to provide high linearity (using a non linear power amplifier such as class E) and to provide relatively high efficiency. This technique is based on the use of one highly efficient, but non linear power amplifier that is used for the phase modulation, together with an envelope amplifier (EA) that has to have high efficiency and provide envelope modulation by modulating the voltage supply of the non linear power amplifier, Figure 1.

The envelope amplifier is a dc-dc power converter that should track dynamically the envelope with accuracy and it is therefore a very challenging circuit. Also, Envelope Tracking (ET) technique requires a fast dc-dc converter to supply power to the power amplifier but, in this case, the PA is linear and the EA can be slower and less accurate because it has to supply the PA with a voltage higher than the envelope in order to avoid the saturation of the output stage of the PA.

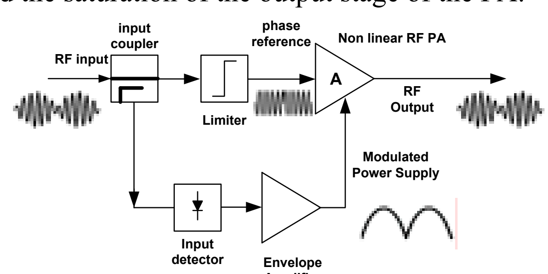

Figure 1. Block schematic of a transmitter based on Kahn's technique

In the state of the art, the use of a classical buck or boost dc-dc converter is very extended [3-5] in low

This work has been supported by the Ministerio de Ciencia e Innovación de España through the project TEC2009-14307-C02-01

power. An interesting modification allows the use a three-level converter [6] reducing the output voltage ripple. However, these circuits use a switching frequency that should be several times higher than the envelope frequency. Therefore, in practice, the maximum bandwidth of the envelope is limited to hundreds of kHz due to the power losses on this envelope amplifier.

The architecture proposed in [7] is composed of a switched dc-dc converter and a parallel linear regulator. Both regulators contribute to provide power to the output. Since the bandwidth of the switched part is limited, it is in charge of the DC value while the much faster linear takes care the AC component. The power losses of the switched part can be very small but the linear regulator penalizes the overall efficiency.

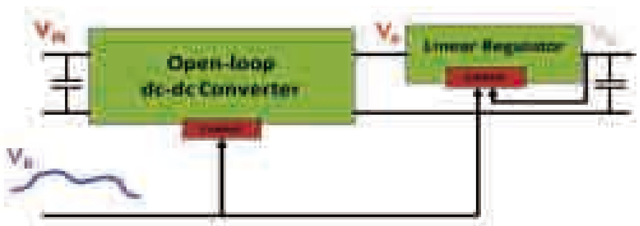

Figure 2. Series association of switched and linear regulators

Other possibility is to use the series configuration shown in figure 2 and proposed in [8]. The role of the switched converter is to reduce dynamically the supply voltage of the linear regulation according to the shape of the reference to reduce the power losses on it. The linear part will receive the same reference and it is the responsible to provide at its output the envelope required by the power amplifier. In terms of efficiency this solution is better than a single linear regulator but it is necessary to obtain quite high efficiency in the switched part.

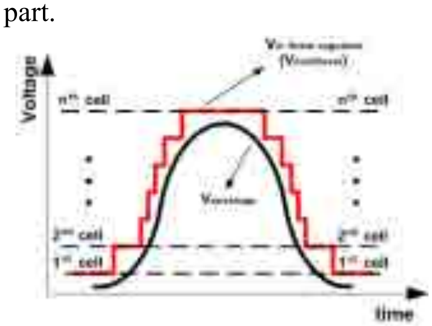

Figure 3. Time waveforms of the switched converter of the envelope

The switched regulator can be implemented in many different ways. However to obtain a good efficiency together with a high bandwidth is necessary to simplify it. Thus, it will operate in open-loop and its output will be only certain discrete voltage levels as shown in figure 3.

II. Implementations of the Switched DC-DC Converter

The switched converter will operate as a multilevel converter and there are several possibilities for its implementation. Four of them will be presented in this paper. In the first three solutions the switching frequency applied in the multilevel converter is significantly lower than in the case when a classical PWM dc-dc converter is used for the EA

A. *Multilevel converter with switching cells*

In this solution several independent voltage cells are combined in series in order to obtain different voltage levels.

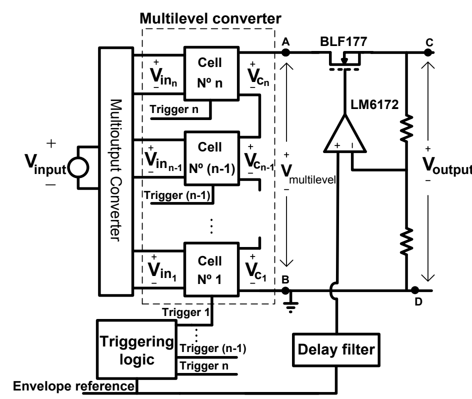

Figure 4. Simplified schematic of the proposed EA using independent voltage cells

Figure 4 shows simplified schematic of the complete EA with the multilevel converter based on switching cells. Each voltage cell can reproduce voltage equal to its input voltage and there can be distinguished two types of cells: unipolar (two-level) and bipolar (three-level) cell, Figure 5.

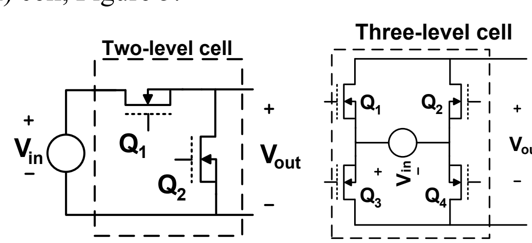

Figure 5. Unipolar (two-level) cell and bipolar (three-level cell)

A.1 Unipolar switching cells

The output voltage of these cells is equal to V_{IN} or 0. The number of the required cells is equal to the number of levels and each cell has two transistors. In principle, the higher the number of levels, the higher the efficiency of the linear regulator but the efficiency of the multilevel converter is decreased due to switching losses. For each specification, this calculation should be done but a small number of levels (i.e. three) used to be good enough.

A.2 Bipolar switching cells

In this case, each cell can provide three values V_{IN}, o and $-V_{IN}$. The total output voltage is the sum of the voltage of each cell so for the same number of levels, less number of cells are required. When a cell is providing a negative voltage it returns power to its input so it should be taken into account. In these two configurations, the switching frequency is equal to the maximum bandwidth required by the envelope while in the classical solution switching frequency needs to be 5 to 10 times higher; therefore, the efficiency of this solution is very good.

B. *Multilevel converter with analog multiplexer*

Another possibility is to use several independent voltage sources and to combine them by an analog multiplexer, Figure 6. Due to the optimization process of the multilevel converter's voltage levels in [8] for high PAPR signals (WCDMA, OFDM, etc.) it is convenient to use simple voltage dividers implemented with switching capacitors, Figure 7.

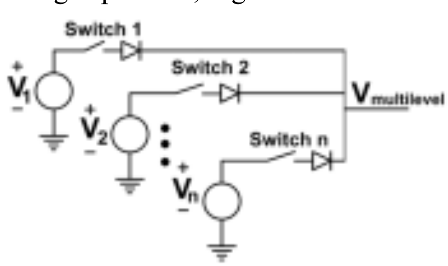

Figure 6. Simplified schematic of the envelope amplifier based on independent voltage sources and an analog multiplexer

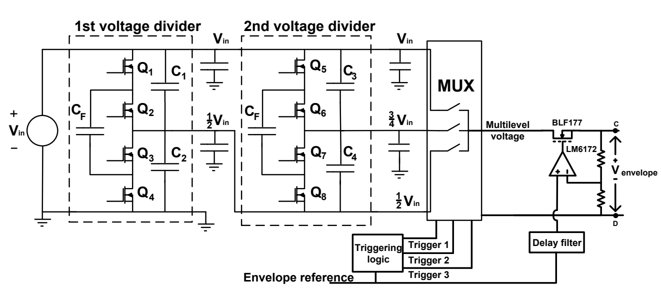

Figure 7. Simplified schematic of the implemented EA based on switching capacitors

The converters based on switching capacitors do not need any bulky magnetic component and it can operate using very low switching frequencies (as low as 50 kHz). The switching frequency of the switches in the analog multiplexer will depend on the type of the transmitted signal and its envelope distribution. For example, in the case when the envelope is a 2 MHz sine wave, the maximum switching frequency in the analog multiplexer will be 2 MHz, as well.

C. *Multiphase buck converter as a multilevel converter*

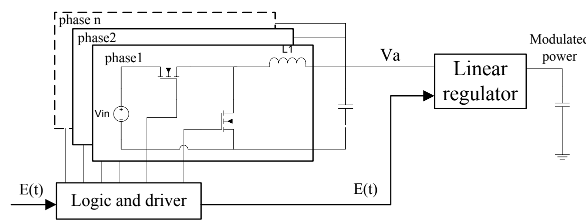

Figure 8. Multiphase converter that acts as a multilevel converter in series with a linear regulator

Multiphase converters can be used for the implementation of the multilevel converter by applying the minimum time transition principle [9]. Thanks to this nonlinear control, very fast transients (faster than one phase switching cycle) can be obtained, but the huge inconvenient of this solution is that it is necessary to have very fast digital clock for accurate control of transition times. Additionally, it does not guarantee correct current sharing among the phases which can lead to lower efficiency than expected. Figure 9 shows the phase currents and output voltage during the transient. It can be observed that the transient is smooth (no over shoot) and very fast (around 1.5 switching cycle).

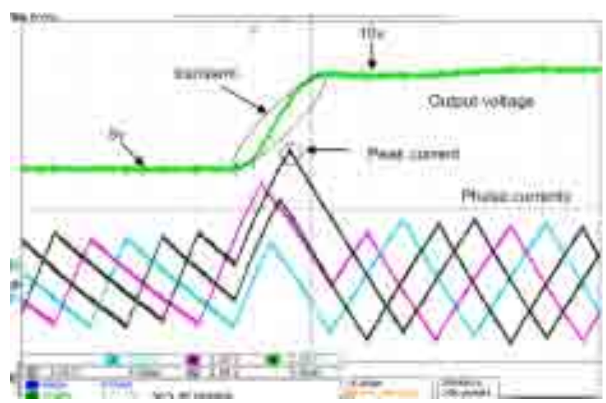

Figure 9. A transient in the multilevel converter implemented with a multiphase converter (4 phases)

III. EXPERIMENTAL RESULTS

Each solution for the multilevel converter has been implemented and verified. Figure 10 shows the output voltage of the multilevel converter using unipolar independent voltage cells and the output voltage of the implemented EA when the envelope is a 2 MHz sine wave.

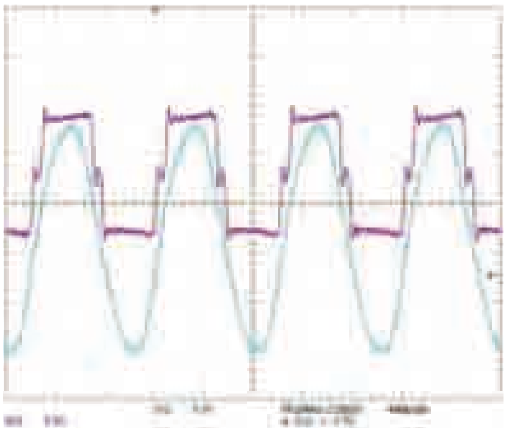

Figure 10. Multilevel output voltage (3 voltage levels) and envelope amplifier's output voltage in the case of a 2 MHz sine wave envelope

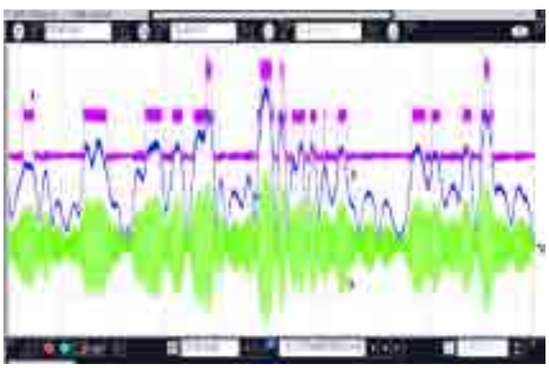

Figure 11. Multilevel voltage, EA outuput voltage and voltage of the implemented EER PA in the case when a 64QAM is applied

Complete PA based on Kahn's technique was implemented using a multilevel convert with unipolar cells as the EA. Figure 11 shows the response of the multilevel converter, EA and complete PA for a 64QAM modulation. The peak power was, approximately 100 W, carrier frequency was 120MHz and the bandwidth of the transmitted signal was 2MHz.

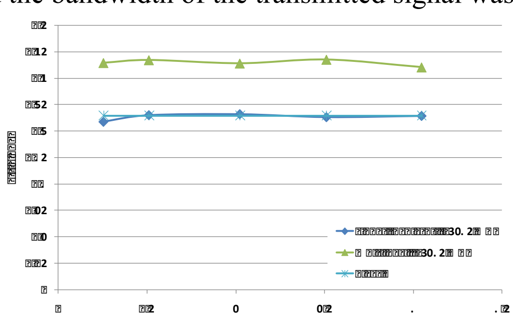

Figure 12. Measured efficiency of the implemented EER PA compared with the linear solutions

Figure 12 presents the drain efficiency of the EER based on a class E amplifier when the linear regulator in the EA is supplied by constant voltage (33%) and when it is supplied by the multilevel converter (43%). Also, the theoretical efficiency of an ideal class B amplifier for the same signal is 33%. By analyzing these results, it can be concluded that the power amplifier that employs the EER technique produces up to 25% less power losses.

IV. CONCLUSIONS

In this paper, a two-stage series configuration for an envelope amplifier has been presented. The first stage is a switched converter and four different configurations have been presented to implement it. This converter works in open-loop and in three of these implementations the switching frequency is smaller than in the classical solution based on a PWM converter. The second stage is a linear regulator that is supplied with a voltage slightly higher than the required envelope reducing its power losses.

Some of these implementations have been tested in an actual EER power amplifier with a 2MHz bandwidth showing a 10% efficiency improvement.

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